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A Novel Liquid Packaging Structure of Deep-Ultraviolet Light-Emitting Diodes to Enhance the Light-Extraction Efficiency

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Abstract: To realize high-efficiency, AlGaN-based, deep-ultraviolet light-emitting diodes (DUV-LEDs), enhancing their light-extraction efficiency and reducing thermal resistance is very crucial. We proposed a liquid packaging structure that could enhance optical power by 27.2% and 70.7% for flat type and lens type 281-nm DUV-LEDs, respectively. A significant improvement effect at different wavelengths, such as 268 nm and 310 nm, was also observed. Furthermore, using the liquid packaging structure, the thermal resistance was reduced by 30.3% compared to the conventional structure. Finally, the reliability of liquid packaging DUV-LEDs was tested. The light output maintenance of liquid packaging DUV-LEDs was compared to the conventional structure.

Keywords: deep-ultraviolet light emitting diode; silicone oil; liquid packaging

1. Introduction

Deep-ultraviolet light emitting diodes (DUV-LEDs) have been attracting significant attention as a new light source that can replace conventional mercury-based UV lamps in disinfection, chemical decomposition, water and air purification, and food safety control [1–3]. Compared to mercury-based UV lamps, DUV-LEDs have more advantageous characteristics, including small volume, easy integration, a long life-time, tunable wavelength, and being mercury-free [2,4]. However, the light efficiency and output power of DUV-LED devices are still low. The highest reported external quantum efficiency (EQE) and power output in the ultraviolet C (UVC) range (200–290 nm) is 14.3% and 153.4 mW, respectively [2,4–8]. On the other hand, the mainstream design of DUV-LED packages uses quartz glass as the cover without an encapsulation material inside the cavity [9]. This kind of package structure reduces the light extraction severely and limits the optical performance of DUV-LEDs [10,11]. To ameliorate these drawbacks, some DUV transparency encapsulation materials have been proposed for the DUV-LED package structure [12–14].

In this study, a liquid packaging structure for DUV-LEDs was developed. The light output was enhanced by 70.7% compared to the conventional package structure. Furthermore, the thermal resistance of the liquid packaging structure for DUV-LEDs was measured. Using the liquid packaging structure, the thermal resistance was reduced by 30.3% compared to the conventional structure. The reliability of liquid packaging DUV-LEDs was also tested. The light output maintenance of liquid packaging DUV-LEDs for 200 hours remained above 98%.

2. Materials and Methods

The Figure 1 illustrates the structures of five different package types (PTs): PT-I is a DUV-LED without a quartz plate, PT-II denotes a conventional flat type DUV-LED, PT-III stands for a conventional lens type DUV-LED, PT-IV is a flat type liquid packaging DUV-LED, and PT-V denotes the lens-type liquid packaging DUV-LED proposed in this study. In Figure 1, the black part is the DUV-LED chip. The blue part is the ceramic substrate with an Au coating. The green part is a quartz cover that has a flat type and lens type. The pink part is silicone oil in the cavity substrate. All the structures are composed of the same chip and ceramic substrate. For the DUV-LED chip, its output power and peak wavelength in the ceramic substrate was about 9.30 mW and 281 nm at 60mA, respectively. The chip size was 250 × 500 × 200 µm. The chip structure was the flip chip type, so we use a refractive index of sapphire of about 1.82 in the UVC range [15] as the light source. The material of the cavity substrate was aluminium nitride and its size was 3.5 × 3.5 mm. A thin film of gold with a reflectance of 38% was plated on the bottom and the top of the cavity. The sidewall was AlN with 16% reflectance. There were two types of quartz plate placed on the top of the substrate. One was flat type and the other was lens type. The size of the flat type quartz plate and lens type quartz plate were 3.3 × 3.3 × 0.5 mm and 3.3 × 3.3 × 1.7 mm.

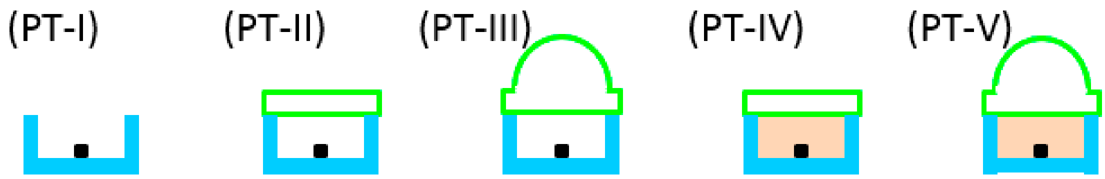

Figure 1. Structure diagrams of the five package types of the Deep-ultraviolet light emitting diodes (DUV-LEDs).

The silicone oil we used in this study was dimethylpolysiloxane, with the part number KF-96-50CS (Shin-Etsu Chemical Co., Ltd, Tokyo, Japan). Its refractive index was 1.487 [16] in the UVC range and its transmission spectrum, shown in Figure 2, was measured by spectrophotometer (model name: U2900, Hitachi, Tokyo, Japan). The result shows that the transmittance of the silicone oil was over 82% from 260 nm to 350 nm. The structure of silicone oil is very simple, it is composed of Si-O and Si-CH_3 functional groups. The main chain of silicone oil is bonded by Si-O, which has a high bonding energy of 108 Kcal/mol. It is not easily broken by UVC and ultraviolet B (UVB) (290–320 nm), since UVC and UVB energy is 102 Kcal/mol and 91 Kcal/mol, respectively. This characteristic makes silicone oil transparent from 260 to 350 nm. In commercial silicone, due to its solid property, some CH_2 functional groups will be added to the main structure to make the main chains longer and the molecular weight higher. When CH_2 functional groups are in the main chain, C-C bonds occur, which have a low bonding energy of 85 Kcal/mol. In addition, some additivities like the phenyl group, UV absorber and hardener are added to the commercial silicone. These additivities will reduce the transmittance in the deep-UV range. In Figure 2, we also added the transmission spectrum of the commercial silicone Dow corning, OE66 series, for comparison in the deep UV region. The high transmittance of this wavelength range (260 nm to 350 nm) of silicone oil is very useful for deep-UV LED packages, since most recent investigations and applications of deep-UV LED are in this wavelength range [1,2,17,18]. For 281 nm, the transmittance of silicone oil is about 94%.

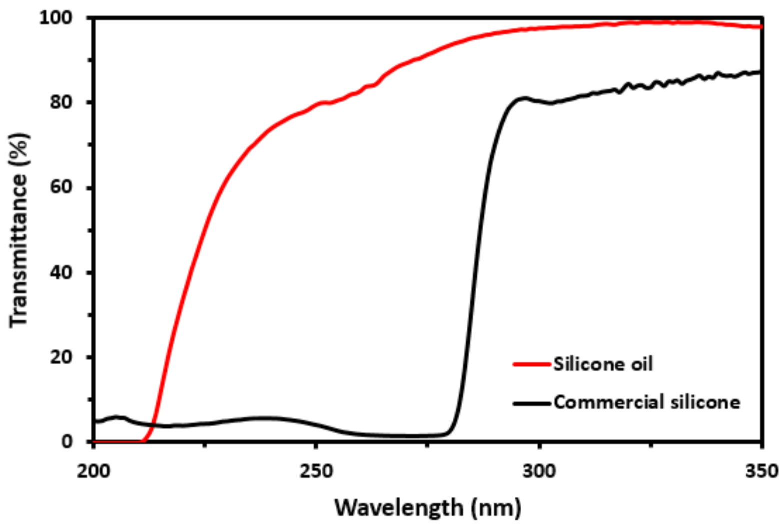

Figure 2. Transmittance of silicone oil.

A ray-tracing simulation was performed using Light Tools™ (Synopsys Inc, Mountain View City, CA, USA). Table 1 lists all the optical parameters of the ray-tracing simulation. The simulation 3D model is shown in Figure 3a and the simulation result is shown from Figure 3b–f. In Figure 3b, the ray-tracing profile for PT-I DUV-LEDs demonstrates that the color of chip part is black, which means that the DUV light (for 281 nm) was trapped inside the DUV chip and only 42.9% of light can exit the DUV chip due to the total internal reflection (TIR) loss resulting from the large refractive index gap between sapphire (the top of DUV chip, n = 1.82) and air (n = 1). After the light exits the chip, the light will be absorbed by a ceramic reflector and the light output is reduced to 34.8%, which is only about 9.30 mW due to low reflectance of AlN and the gold plating (reflectance of 16% for AlN and 38% for Au in the deep-UV range). In Figure 3c, the ray-tracing profile for PT-II DUV-LEDs shows that the light output will be reduced by 13% to 8.04 mW through the flat type quartz plate. We found that even though we changed the quartz plate from the flat type to the lens type shown in Figure 3d, the light output cannot be increased significantly, and could only be increased from 8.04 mW to 8.24 mW, a 2.5% enhancement. The ray-tracing profile and power simulation results for PT-IV and PT-V DUV-LEDs are shown in Figure 3e,f. It is obvious that the color of the chip is not black, which means that the DUV light generated from the chip exits easily. Compared to the PT-I DUV-LED, the light output was improved by 17.0% for PT-IV and by 70.6% for PT-V due to the silicone oil inside the cavity. Comparing the different packages with and without silicone oil, we found that the light output power was enhanced by 35.3% from 8.04 mW to 10.88 mW for the flat type (PT-II and PT-IV) and by 92.6% from 8.24 mW to 15.87 mW for the lens type (PT-III and PT-V). This light extraction enhancement is attributed to the reduction of TIR loss. There was no encapsulation layer between the chip and the quartz plate for the conventional DUV-LED structure, thus the DUV light was trapped in the chip. The simulation results showed that the light output could be significantly improved using this liquid type structure, especially for the lens type DUV-LED.

Table 1. Optical parameters of the components of the proposed DUV-LED.

Component	Optical Parameters
Chip	Refractive index: 1.82 for sapphire [15] Surface: Fresnel loss
Substrate	Reflectance: 16% for AlN surface Reflectance: 38% for Au surface
Quartz	Refractive index: 1.492 [19]; Transmittance: 95% @ 10 mm Surface: Fresnel loss
Silicone oil	Refractive index: 1.487 Transmittance: 94% @ 10 mm Surface: Fresnel loss

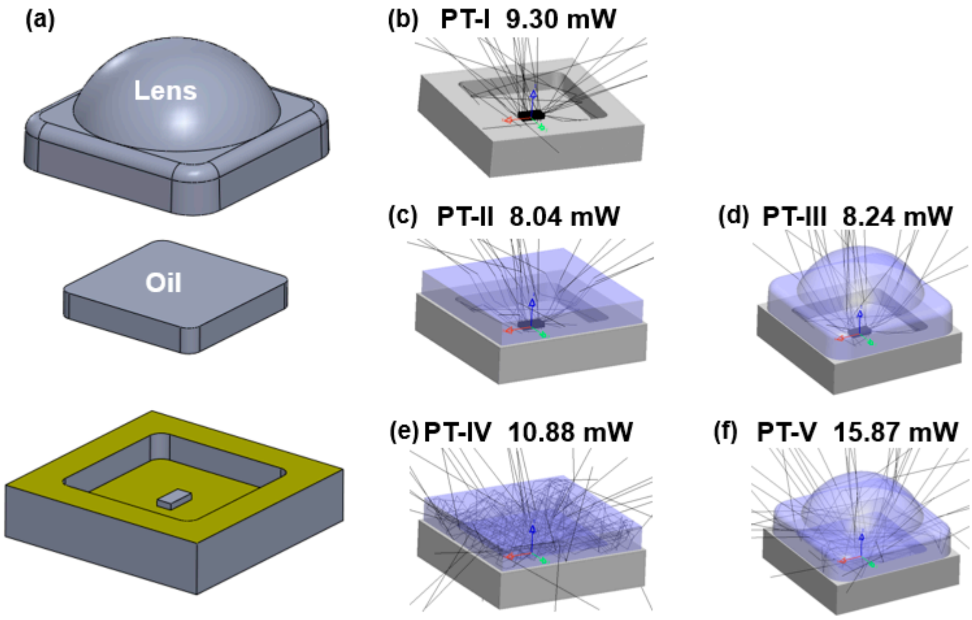

Figure 3. (**a**) 3D model for the simulation, and the simulation results for the output power for (**b**) PT-I, (**c**) PT-II, (**d**) PT-III, (**e**) PT-IV, and (**f**) PT-V DUV-LEDs.

3. Experiment and Results

3.1. Fabrication

The packaging process of the proposed DUV-LED is illustrated in Figure 4. First, we prepared a ceramic substrate whose electrode and reflectance material are gold, see Figure 4a. Second, we bonded the peak wavelength 281 nm DUV-LED chip to the ceramic substrate using a soldering bonding process, as shown in Figure 4b. Additionally, the bonding picture of the 281 nm, 250 × 500 µm DUV-LED chips is also illustrated in Figure 4b. Then, we filled the silicone oil (part number: KF-96-50CS, Shin-Etsu Chemical Co., Ltd., Japan) into the cavity, see Figure 4c. After that, in Figure 4d we placed and sealed the flat type quartz plate onto the substrate with the sealing condition at 80 °C for 30 minutes. The lens type of the DUV-LEDs in Figure 4e was prepared the same way.

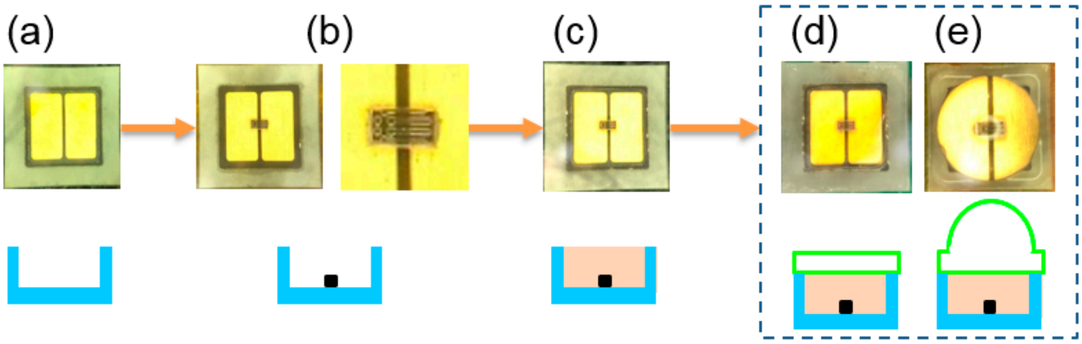

Figure 4. Packaging process of the liquid-package PT-IV and PT-V DUV-LEDs.

3.2. Optical Measurement Results

In this part, we tested the optical performance of three different wavelength chips (281 nm, 268 nm, and 310 nm) in five different package structures, described in Figure 1. The chip layout and spectrum at 60 mA for three different wavelength chips are shown in Figure 5. These chips were all flip chip type and their sizes were 250 × 500 µm, 760 × 760 µm, and 500 × 500 µm for 281 nm, 268 nm, and 310 nm.

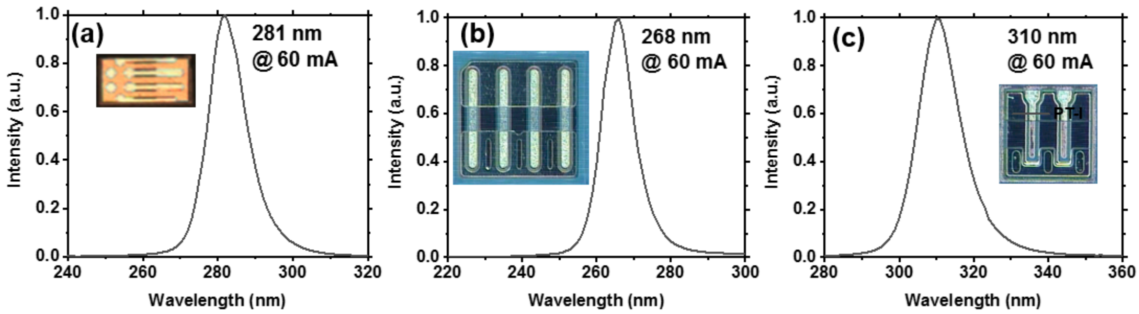

Figure 5. Three different wavelength DUV-LEDs and their spectra at 60 mA.

The results for the optical power of the five PT DUV-LEDs were measured using an integration optoelectronic testing system (model name: 58158S, Chroma, New Taipei City, Taiwan) and are shown in Figure 6 and Table 2. The results showed that using the conventional package methods, the optical power of 9.30 mW (PT-I) was reduced by 15.1% to 7.90 mW for PT-II, and by 10.2% to 8.35 mW at 60 mA for the PT-III DUV-LEDs. With silicone oil inside the cavity, the light output was significantly enhanced, especially for the lens type structure (PT-V). For the flat type structure, from PT-II to PT-IV, the light output was increased by 27.2%, from 7.90 mW to 10.05 mW at 60 mA. For the lens type structure, from PT-III to PT-V, the light output was increased by 70.7%, from 8.35 mW to 14.25 mW at 60 mA. The measurement results showed the same trend as the simulation results described above.

Table 2. Optical power and EQE results for different types and different wavelength DUV LEDs at 60 mA.

Packagetype	281 nm		268 nm		310 nm	
	Power (mW)	EQE (%)	Power (mW)	EQE (%)	Power (mW)	EQE (%)
PT-I	9.30	3.52	6.28	2.26	10.84	4.52
PT-II	7.90	2.99	5.06	1.82	9.56	3.98
PT-III	8.35	3.17	5.30	1.90	9.88	4.12
PT-IV	10.05	3.81	6.50	2.34	11.96	4.98
PT-V	14.25	5.39	8.68	3.12	16.52	6.89

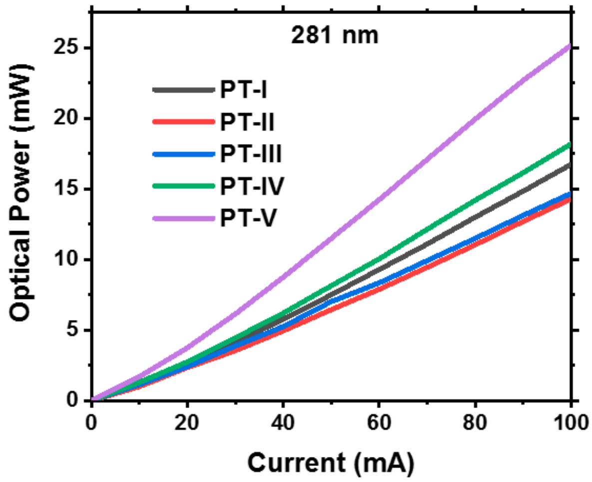

Figure 6. Optical power of 281 nm five PT DUV-LEDs.

The light improvement effect at different wavelengths, such as 268 nm and 310 nm, was also tested. The light output results for 268 nm and 310 nm are shown in Figure 7 and Table 2. Similar result to those for 281 nm were observed. For 268 nm, we used a 760 × 760 µm flip chip as the light source. Figure 7a shows that the conventional structure of a 268 nm DUV-LED, regardless of whether it had a flat type or a lens type quartz, the light output of 6.28 mW would be reduced by 19.4% to 5.06 mW and by 15.6% to 5.30 mW at 60 mA, respectively. With silicone oil inside the cavity, for the flat type structure the light output was increased by 28.5%, from 5.06 mW to 6.05 mW at 60 mA. For the lens type structure, the light output was increased by 63.8%, from 5.30 mW to 8.68 mW at 60 mA. For 310 nm, we used a 500 × 500 µm flip chip as the light source. Figure 7b showed that the conventional structure, regardless of whether it has a flat type or a lens type quartz, the light output of 10.84 mW was reduced by 11.8% to 9.56 mW and by 8.9% to 9.88 mW at 60 mA, respectively. With silicone oil inside the cavity, for the flat type structure the light output was increased by 25.1%, from 9.56 mW to 11.96 mW at 60 mA. For lens type structure, the light output was increased by 67.2%, from 9.88 mW to 16.52 mW at 60 mA. The light output and EQE results for the different wavelength and different structure are presented in Table 2. The enhancement ratio of the liquid packaging DUV-LED compared with a DUV-LED without a quartz plate on the top increased with the increased wavelength. This might be due to the transmittance and reflectance of all the components in the DUV-LED package, such as the AlN sidewall, gold plating, quartz plate, and silicone oil, which increase with the increasing wavelength.

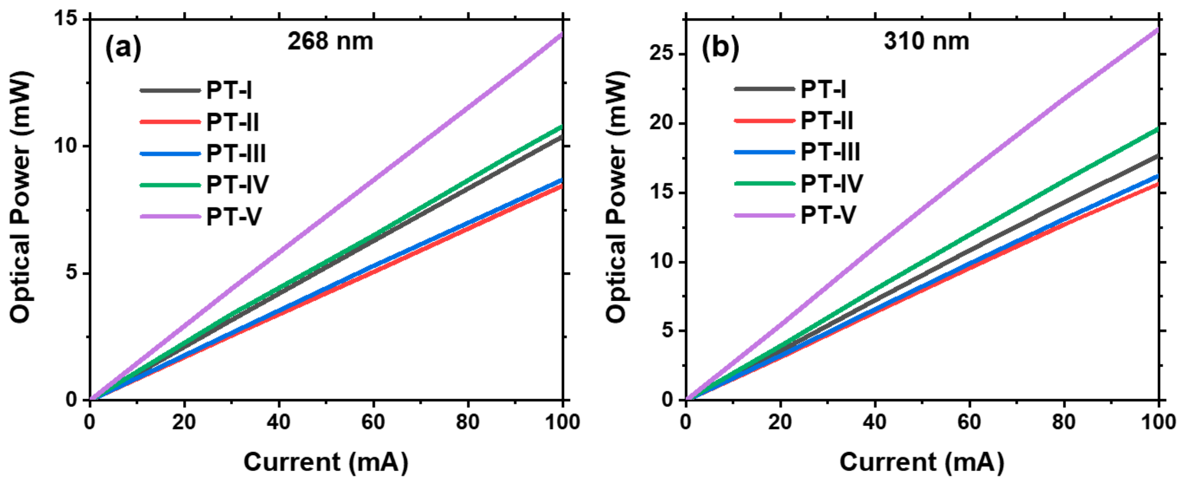

Figure 7. Optical power of the five PTs for (**a**) 268 nm and (**b**) 310 nm DUV-LEDs.

3.3. Thermal Resistance Measurement Result

As the PT-V showed the best optical performance, the PT-V and its counterpart the PT-III were the focus of the following research.

Some papers have shown that there is great potential for the use of silicone oil as a heat transfer material [20–22]. Some studies have shown that the reduction of thermal resistance could be up to 30% [22] using a liquid type structure for UVA LED. Since the EQE of DUV-LEDs is still low, the thermal management of DUV-LEDs is very important. The thermal resistance of liquid packaging DUV-LEDs was also measured using a T3Ster system (Mentor, USA), and the results are shown in Figure 8. The thermal resistance of the conventional structure of the 281 nm DUV-LED package was 28.98 K/W, as shown in Figure 8a. The thermal resistance of the liquid packaging structure of the 281 nm DUV-LED package was 20.21 K/W, as shown in Figure 8b. The reduction of the thermal resistance using the liquid packaging structure was 30.3%, which is very similar to previous work [22]. Thermal resistance reduction due to silicone oil was also observed for the DUV-LED package in this study. Referring to the heat dissipation mechanism of the liquid packaging from the previous study [23], the major route of the heat generated from the chip was not through the top of the LED package, thus a comparison of the thermal resistance for the flat type and lens type was not carried out here, and only the DUV-LED package with or without silicone oil was discussed.

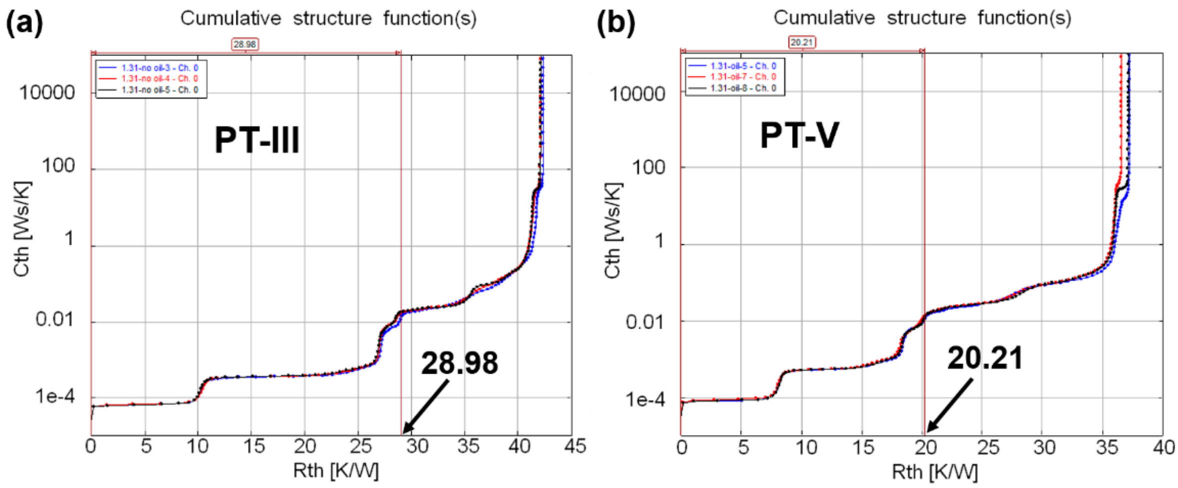

Figure 8. The thermal resistance for 281 nm (**a**) PT-III and (**b**) PT-V DUV-LEDs.

3.4. Reliability Test Results

The light maintenance of the 281 nm liquid packaging DUV-LEDs for 200 hours was tested, and the results are shown in Figure 9. PT-V-Max, PT-V-Avg, and PT-V-Min represent the maximum, average, and minimum value of the light maintenance of the liquid packaging PT-V DUV-LED, respectively. PT-III-Max, PT-III-Avg, and PT-III-Min represent the maximum, average, and minimum value of the light maintenance of the conventional PT-III DUV-LED, respectively. We tested five samples for each PT-III and PT-V DUV-LED to compare the reliability results with and without the liquid packaging design. The test environment was at room temperature of 25 °C and the driving current was 60 mA. The result shows that the average light maintenance of the liquid packaging DUV-LED and conventional DUV-LED was 98.5% and 96.6%, respectively. The light maintenance of both structures was at the same level, and the liquid packaging PT-V DUV-LED performed better than conventional one. This implies mass production possibilities for this liquid packaging PT-V DUV-LED.

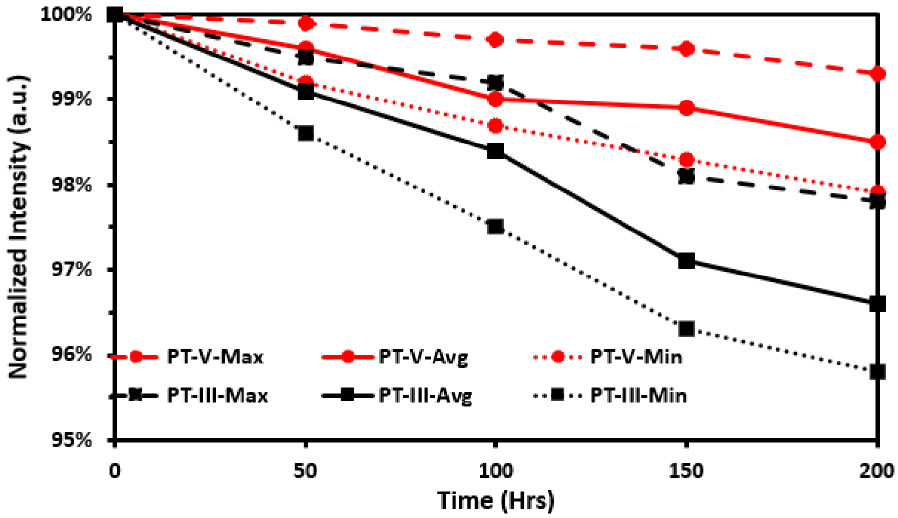

Figure 9. Reliability test results for 281 nm PT-III and PT-V DUV-LEDs.

4. Conclusions

In this study, we introduced a simple fabrication method to improve the light output power of DUV-LEDs. Using silicone oil as the encapsulation material for DUV-LED packages, its process was very similar to that of white light emitting diodes. This increases the possibility of a wide range of DUV-LED applications. Due to the low EQE of DUV-LEDs, enhancing their light output and reducing thermal resistance is very crucial. In this study, we compared the optical power of different package designs with and without silicone oil inside the cavity. For the flat type and lens type package structures, the optical power and EQE were significantly enhanced by 27.2% and 70.7% for 281 nm DUV-LED, respectively. This liquid packaging structure was also workable for 265 nm and 310 nm DUV-LEDs. With silicone oil inside the cavity, the optical power and EQE for 268 nm and 310 nm were improved by 28.5% and 25.1% for the flat type, and by 63.8% and 67.2% for the lens type, respectively. Furthermore, using the liquid packaging structure, the thermal resistance was reduced by 30.3% compared to the conventional structure. The 200-hour reliability test showed that the liquid packaging DUV-LEDs had good thermal and DUV resistance. The proposed liquid packaging structure is feasible as a compact structure with high light extraction efficiency and promising good thermal management of DUV-LED packaging, and it may inspire new packaging structures and methods for DUV-LED devices.

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Conflicts of Interest: The authors declare that there are no conflicts of interest related to this article.

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